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Influence of the use/user profile in the LCA of 3d printed products

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Abstract

Personal Fabrication (PF) is becoming more popular each day and as all disruptive technology, its environmental impacts are still little known. A number of authors have tried to compare PF and Industrial Manufacturing (IM) using Life Cycle Assessment (LCA) but, opposite results are found among these studies. This paper presents another study that compared PF and IM using LCA. The findings suggest that this comparison is debatable and that, besides the technical aspects, an important issue has to be considered in the LCA of 3d-printed products: the use/user profile. Conclusions show that 3d-printing use/user profile has a direct and important participation in the whole of environmental impacts of printed products and that any LCA of PF that neglects these aspects seems to be incomplete and debatable.

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1. Introduction

Since the Industrial Revolution in the 19th century, the production of goods is synonymous of heavy industry, machine tools, production lines and economies of large scale [1]. Nowadays, several reports and researches show that many important environmental problems as global warming affecting our planet ecosystems are due to pollutions, such as greenhouse gas emissions released by our industrial manufacturing systems in the atmosphere.

Industrial Manufacturing (IM) although recognized as one of the biggest cause of the environmental impacts, works to satisfy the population consumption standard. To attend the personal desires of the consumer is a new challenge for the IM but it is also becoming a business opportunity to enterprises and market, especially because of the product customization trend. According to Bouffaron [1] modern consumers now require highly customized products, fast service, and a lightning delivery.

Facing economics world changes, this new consumption trend has pushed the concept of Personal Fabrication (PF), a type of manufacturing that allows producing customized

products according to each consumer's desire. This new approach to manufacturing is considered nowadays by many authors as the "New Industrial Revolution". Morris [2] states that this revolution in manufacturing may be coming sooner than we expected and it could change the role of industrial design dramatically.

As all disruptive technology, PF is breaking many manufacturing paradigms and a number of authors have tried to compare it with Industrial Manufacturing (IM) using Life Cycle Assessment (LCA) in order to define which system is 'greener'. But that comparison in the majority of the cases seems doubtful and debatable. It is possible to find results in which PF is presented as better than IM regarding environmental impacts, but also opposite results.

This paper brings forward a brief literature review about these contradictory results from different authors and presents another experience using LCA that compares environmental impacts (EI) of two similar products, one made in industry and the other one made using a 3d printer. The analysis will show that besides technical aspects such as 3d-printer machines, energy consumption, material, etc., there is another important

factor to be considered in a LCA of printed product that is overlooked in many studies: the use/user profile.

Finally, this study will present the analysis/results of four hypotheses launched in the LCA to measure the influence of use/user profile in the whole of environmental impacts with unexpected and important findings.

2. Personal Fabrication

According to Morris [2], Personal Fabrication (PF) is the manufacturing of a product using a personal computer, digital data and a 3d-printer that can produce three-dimensional solid objects. For Gershenfeld [3] this concept is wider, the author says that PF ‘means not only the creation of three-dimensional structures but also the integration of logic, sensing, actuation, and display – everything that is needed to make a complete functioning system’.

Because of 3d printers and Computer Aided Design evolutions, PF becomes more popular each day and is used for different purposes: to construct human prosthesis and houses or simply toys and personal products. These products are made using a 3d printer, a machine apparently complex regarding its technology, but simplistically defined by Anderson [4] in this sentence: ‘we can imagine something, draw it on a computer and a machine can make it real.’

Straightening this, Bouffaron [1] declares that personal fabrication technologies provide the ability to manufacture practically all kinds of equipment and objects in a wide variety of material. ‘From a personal computer any professional or *maker* can create a digital representation of an object or simply download it online and then see it taking shape in a 3d printer’.

In this viewpoint, we note that the term ‘maker’ refers to persons who make or manufactures objects with their own hands developing the whole process; it is related to the DIY (Do It Yourself) movement [5]. It is not a new concept but it is increasing with the digital revolution. According to Anderson [4], it is time to return ‘making things’ and ‘get your hands dirty again’. The author states that a new generation of designers and manufacturing entrepreneurs should be created to go along with this new revolution.

3. Personal Fabrication vs Industrial Manufacturing

Some authors have tried to compare Personal Fabrication (PF) and Industrial Manufacturing (IM) using Life Cycle Assessment (LCA) in order to try to define which system is the ‘best’ for the environment. In some studies authors found that PF is globally better than IM and in the others the results are opposite.

Kreiger *et al* [6] in their comparative study declare that ‘the environmental impact of distributed manufacturing with 3-D printers of polymer objects is less than conventional when using PLA (Polylactic acid)’. They state that, ‘with PLA, 3D-printing always had a better environmental performance than conventional mass-manufacturing’, both using less energy and emitting less carbon. In contrast to this study, Faludi *et al* [7] state that the relative sustainability of 3d-printer vs CNC machining depends primarily on the usage profiles, and then on the specific machines. It cannot be categorically stated that 3D

printing (using ABS plastic) is more environmentally friendly than machining or vice-versa. About these two studies, it is important to highlight that there are a wide number of hypothesis involved in each study and each author probably are right in their conclusions.

Other studies do not do a comparison between PF and IM, however, they present Personal Fabrication as a positive transformation for society or sometimes as a ‘green technology’, two aspects refused by other authors. According to Olson [8] ‘enthusiasts are quoted predicting that 3-D printing will make conventional factories and warehouses obsolete and empower people everywhere to become inventors, entrepreneurs, and manufacturers’. Lipson *et al* [9] declare that ‘PF technologies will profoundly impact how we design, make, transport, and consume physical products and Koff *et al* [10] state that ‘PF is simpler, cheaper, smaller and more convenient to use than traditional manufacturing technology; provide an efficient use of raw materials and use of biodegradable plastic’.

On the other hand, Decker [11] states: ‘when billions of people are just a click away from getting factories to work for them, whether in the cloud or on their desktops, this does not be well for sustainability; we will create even more stuff, and each product will cost much more energy than if produced with conventional methods’. Wilson [12] quoting Timothy Gutowski, Professor of Mechanical Engineering at the Massachusetts Institute of Technology (MIT) says that ‘there is a lack of strong evidence or research that suggests that 3D printing is going to lead to a more widespread sustainable society; in fact, in some cases it may have the opposite effect’; another waste problem might be generated if everybody starts printing out 3D objects without thinking it through.’

All these statements are surely based on author’s particular experiences and it is impossible to define who is right or wrong, however, given that these announcements were published in papers and media articles, the level of incertitude about how good is PF for the environment just increases.

There are still others studies about PF that present more reflexive and less affirmative conclusions. Kothala *et al* [13] declare that ‘currently, no evidence-based handbooks or manuals exist on how to conduct or organize environmentally-sound makerspaces or activities. They say: ‘there is a real/clear need for targeted research on the environmental impacts of Personal Fabrication technologies and materials. With the same point of view, Ford *et al* [14] state that ‘the current lack of understanding about how AM-based production systems and value chains will affect overall resource consumption indicates that greater studies are required if we are to gain a more informed view of the sustainability impacts of AM implementation’. Finally, Wilson [12] quoting Dr. Bert Bras, Professor of Mechanical Engineering at the US Georgia Institute of Engineering says that ‘to look for evidence of environmental benefits of Personal Fabrication, sustainability professionals have to seek proof using ISO 14001 standard Life Cycle Analysis (LCA)’.

All these conclusions about Personal Fabrication, sometimes convergent and sometimes not, come forward the necessity of new reflections about it. In the next paragraph, we will present another comparison between PF and IM using

LCA with outcomes that confirm this fragility and encourage posterior analysis.

4. Experiment: Life cycle analysis of a plastic mug

4.1. Materials and Methods

This experiment consisted in the comparison of Industrial and Personal Manufacturing through a Life Cycle Assessment (LCA) to find out clues which may indicate what production system is globally better for the environment and in which aspects. It was performed using the software SIMAPRO 8 and the method of calculation 'Impact 2002+'.

For this study, the following Functional Unit (FU) was defined: Containing 250ml of cold water, 4 times per day, during 3 years. To reach this FU and to compare two products, a plastic mug made in Polyamide (PA) manufactured in Thailand (Figure 1) was acquired and a similar product was designed and printed using Polylactic Acid (PLA) (Figure 2 a,b,c) at Gi-Nova/G-SCOP Laboratory/Grenoble INP, in Grenoble-France. The FU was defined just to provide conditions to carry out the experiment, but PLA is not indicated to make a product that will have contact with foodstuffs. That is the reason why a sensitive analysis related to the material was also conducted using a nylon to contact with food or beverages and results differences were not significant.



Fig. 1. Mug made in the industry



Fig. 2. (a) CAD, (b) Printing Process, (c) Printed mug

4.2. Life Cycles, study boundaries and data inventory

In the IM mug life cycle (Figure 3), the Production phase considered material, transport, energy consumption and injection process. Concerning energy consumption, the value used depended on data given by Thiriez [15] to characterize injection processes. The Distribution phase was entirely considered (Thailand to France) and transport mileage were estimated using specialized websites. The Use phase was not considered because water consumption and soap for the cleaning are supposed to be the same for the two different mugs. Finally, the End of Life phase was designed regarding the fact that Polyamide is not recycled in Grenoble-Fr, therefore, people will discard the mug to municipal waste.

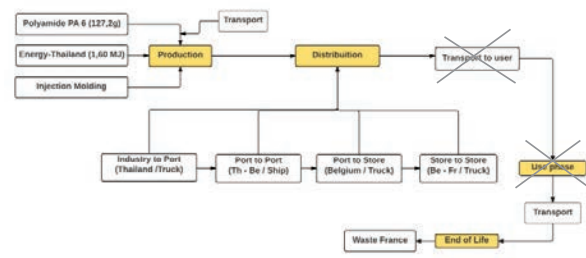


Fig. 3. Life Cycle of a mug made in industry

Regarding Personal Fabrication, in order to carry out the LCA of the printed mug, a process called '3d-printing' was created and inserted in the SIMAPRO database. This process considers the eight groups of machine components with its respective materials, transport and end of life phases, moreover the printer lifetime (2000h) and the energy consumption of a 3d-printer Prusa i3. (Figure 4)

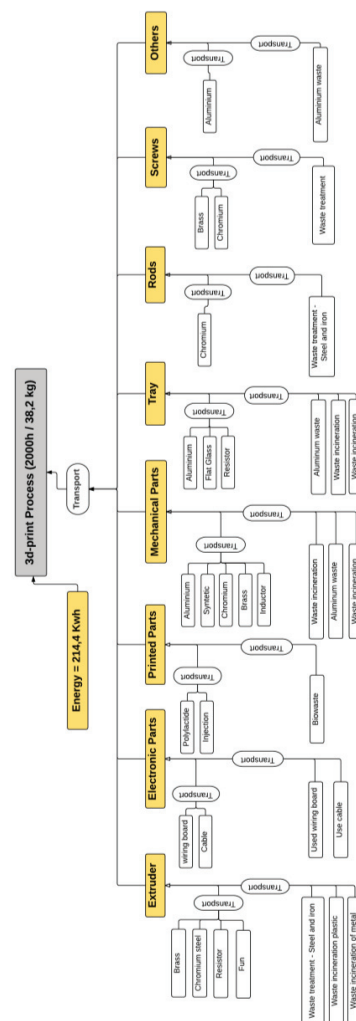


Fig. 4. 3d-Printing process

The whole life cycle of the printed mug (figure 5) consists in 3d-printing process (machine + energy consumption) computer use, material (PLA Filament + Bobbin) and the transports for each stage. The Distribution and the Use phases are not considered and the same hypothesis for IM is used for the End of Life.

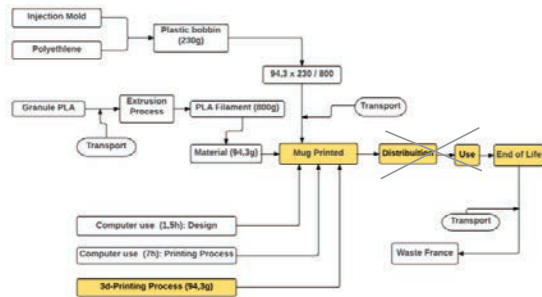


Fig. 5. Life Cycle of a printed mug

4.3. Results and Discussions

Back to the literature, it can be observed that, in most of the cases, comparisons made between IM and PF are focused just on technical aspects such as machine type, material, energy consumption, distribution, etc. As already exposed previously, regarding the environmental impacts of PF, it is possible to find studies that show PF as less environmentally harmful than IM, but also a couple of studies that refuse this conclusion.

Actually, the matter is not clear and finished. The wide number of possible scenarios and results according to each author hypothesis is probably the first reason for the lack of sync among these studies. Furthermore, another point that seems to complicate even more this comparison is about the differences of systems. IM and PF have each one distinct functions and specific goals and this in turn becomes this comparison sometimes doubtful.

Bearing in mind these premises and searching for a more realistic result, this study tries to identify where the cause of the environmental impacts of PF lies and why these impacts are sometimes bigger and sometimes smaller than Industrial Manufacturing. In this perspective, it has been observed that, even though the technical aspects (material and machine type, for instance) have an important participation in the EI, the 3d-printing use/user profile have as well a high contribution and might change severely the results as already announced by Faludi *et al* [7].

In order to better understand the importance of that aspect in the LCA of printed product, four sensitivity analyses were considered to conduct this studies: The first one compares the life cycle of a mug made in the industry and the one made by a 3d-printing expert user (someone who manages very well the CAD and the printer machine). The second hypotheses compares the industrial manufacturing and a beginner user, that is, someone that is starting to use CAD and printers. The third one is just focused on computer use time and compares an expert and a beginner user in CAD skills. Finally, the fourth hypotheses compares also an expert and a beginner on the use of 3d-printers machines.

For the first hypothesis, it was considered a 3d-printing expert user somebody who spent 1,5h in CAD process, 7h of printing process and generated 20g of waste for print a mug. Results showed in figure 6 indicated that environmental impacts generated by Personal Fabrication overcome Industrial Manufacturing in 9 categories, what might suggest that PF generates globally more environmental impacts than IM.

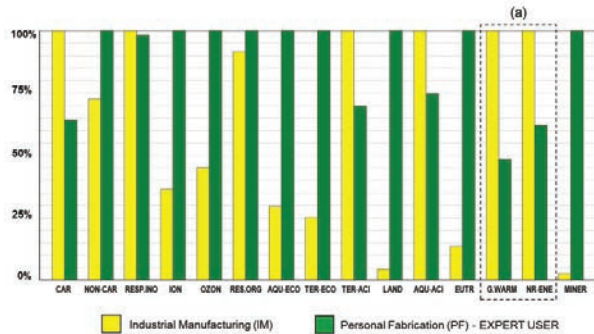


Fig. 6. IM vs PF-Expert user

On the other hand, it can be also observed that although IM overcomes PF just in 6 categories, between them is Global Warm and Non-renewable energy (a), two impact category considered as a key factor in many industries today.

In this first analysis, regarding the compromise between the number of impacts and the importance of each impact, it is not possible to make an accurate assumption about what system is more or less harmful to the environment, mainly because Global Warm and Non-renewable energy categories are too important to enterprises.

Analyzing the second hypothesis, i.e., a beginner 3d-printing user (12h-CAD/22-printing/210g-waste) vs IM, the results are really important to PF. Figure 7 shows that Personal Fabrication can be widely more harmful to the environment when managed by beginner users. It overcomes IM in the 15 impacts categories, including Global Warm and Non-Renewable energy categories (a), an unexpected and surprising result.

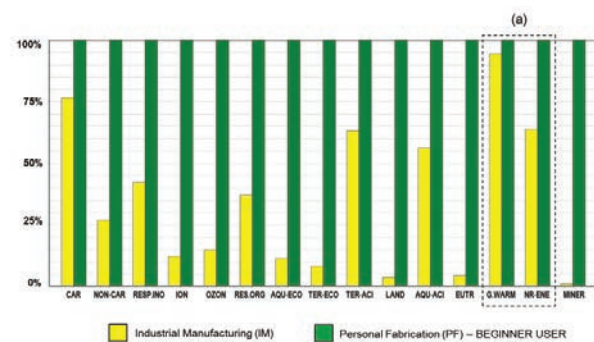


Fig. 7 – IM vs PF-beginner user

According to the IPCC (Intergovernmental Panel on Climate Change) [16], the sectors of Industry and Energy will be the main agents of the Global Warming over the next 50 to 100 years (Fig 8). Therefore, realizing that PF, a small and

individual manufacturing system, may overcome IM in Global Warming and Non-renewable impact categories because of a non-expert use, reinforce the importance to carry out deeper investigations concerning the usage of those new technologies and indicates that the replacement of traditional manufacturing technologies by additive manufacturing needs viability studies from the environmental point of view.

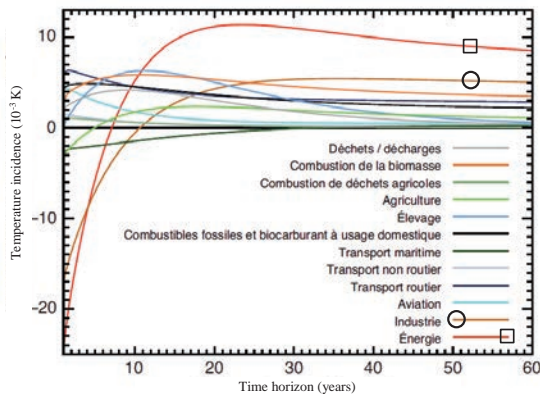


Fig. 8 – Global Warming impact by sectors (IPCC, 2013)

In order to identify the importance of the computer use time in the whole of environmental impacts, a third hypothesis was carried out considering two different CAD users level, one expert and another beginner. Figure 9 shows that a CAD beginner user (12h of computer use to design a mug) generates about 21% more impacts than a CAD Expert user (1,5h of computer use). In addition, for a beginner user, the CAD process represents about 18% of global impacts while for an expert user, this process represents about 3,5% of global impacts.

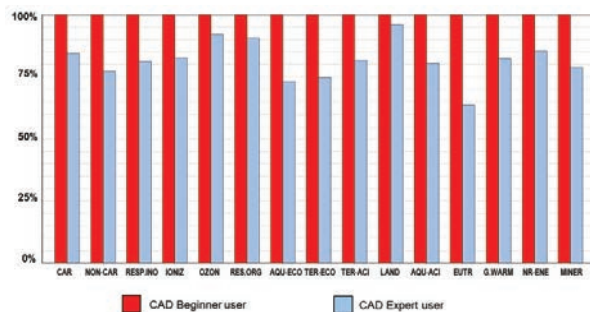


Figure 9 – CAD expertise comparison

In this third hypotheses, another unexpected result concerns the verification of how computer use time brings impacts to a printed product. In general, LCA of Additive manufacturing found in literature are just focused on 3d-printers machines and their energy consumption. This result showed that the product design as well as the user's CAD expertise level (affecting the computer use time) can make a real difference in the global impacts and must be always considered in any LCA.

The last hypothesis was performed to identify the importance of printing time in the whole environmental

impacts. Globally, in the 15 impacts categories, the printing beginner user (22h of printing, 200g of waste to print one mug) generates about 40% more impacts than a printing expert user (7h of printing, 20g of waste) (Fig. 10).

Although these results are predictable, they are quantified (more than 50% of impacts for most of the impact categories) and show that the way how people use the machine is really more important than the environmental cost of the machine itself. This fact bring to light the necessity of novices users be assisted by experts users in their activities in FabLabs, institutions, etc., and this, in turn, enhances the social character of 3d-printing technology and makerspaces.

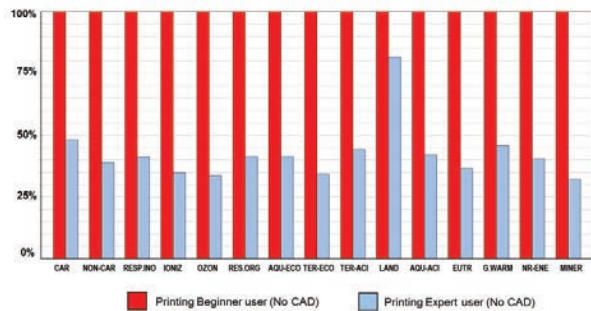


Figure 10 – Printing expertise comparison

In general, these four hypothesis showed clearly that the 3d-printing use/user profile has a direct and important participation in the whole of environmental impacts of printed products. Therefore, the evidences presented in this study indicate that any study about environmental impacts of PF that neglects that aspect seems to be incomplete and debatable.

Finally, it was also noted that there is a direct and logical relation between the user expertise evolution and the waste generation and energy consumption, i.e. when the novice user becomes an expert, the environmental impacts of his activity is reduced, in both aspect, CAD and Printing, as showed in figure 11.

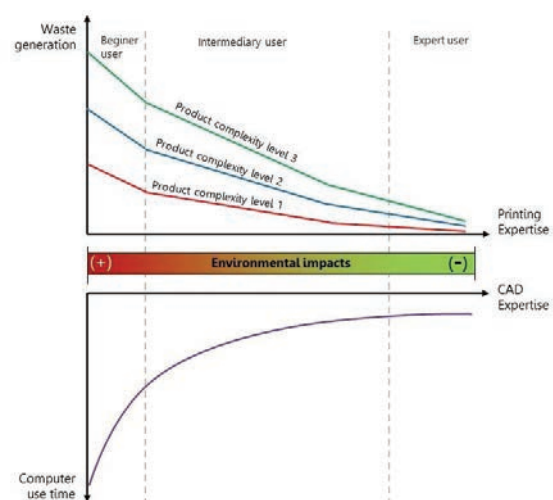


Figure 11 – Expertise level x impact generation

In this context, it can be observed that this is a natural evolution experienced by all users and the waste/time spent in early stages are also important for their progress. If this evolution is deeply studied (objectives, motivations, time, etc.), it will be possible to understand how the users drive the environmental issues in their printing activities. Then, we will be able to design a set of information and procedures for each specific learning stage to indicate the best environmental way to use a 3d-printing technology.

5. Conclusions

In order to find out clues about environmental impacts of Personal Fabrication and to compare the results with others described in the literature, an experiment was performed using Life Cycle Assessment (LCA), which aimed to compare the environmental impacts of two products: two mugs. The first one made in the industry (Thailand) and the other one made in Gi-Nova Laboratory/Grenoble-France using a 3d-printer.

The comparison made between the impacts of the both mug's life cycles showed differences between the two production systems but they are not enough significant or in line to make an accurate conclusion about what system is more or less harmful to the environment regarding the technical aspects such as machine type, material, energy, etc. Indeed, another factor was identified as perhaps more important than technical aspects: the use/user profile.

Among the findings, two unpredicted and important verifications: 1) the environmental impacts of a printed product made by a beginner user (CAD and Printing) may overcome Industrial Manufacturing in 15 impacts categories, including Global Warm and Non-Renewable energy. 2) The computer use time (Design phase), sometimes not considered in LCA of Additive Manufacturing, can make a real difference in the global impacts and must be always considered in any LCA.

Overall, the 3d-printing use/user profile drives the use of computers and printers and this in turn, have a direct and important participation in the whole of environmental impacts of a printed product. The evidences presented in this study indicated that any study about environmental impacts of PF that neglects the use/user profile seems to be incomplete and debatable.

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